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Cognitive Aging in the Seattle Longitudinal Study: Within-Person Associations of Primary Mental Abilities with Psychomotor Speed and Cognitive Flexibility

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Abstract: It has long been proposed that cognitive aging in fluid abilities is driven by age-related declines of processing speed. Although study of between-person associations generally supports this view, accumulating longitudinal between-person and within-person evidence indicates less strong associations between speed and fluid cognitive performance. Initial evidence also suggests that cognitive flexibility may explain within-person variability in cognitive performance. In the present study, we used up to nine waves of data over 56 years from a subsample of 582 participants of the Seattle Longitudinal Study to examine (a) within-person associations of psychomotor speed and cognitive flexibility with cognitive aging in primary mental abilities (including inductive reasoning, number ability, verbal meaning, spatial orientation, and word fluency); and (b) how these within-person associations change with age. In line with the processing speed theory, results revealed that within persons, primary mental abilities (including fluid, crystallized, and visualization measures) were indeed associated with psychomotor speed. We also observed age-related increases in within-person couplings between primary mental abilities and psychomotor speed. While the processing speed theory focuses primarily on associations with fluid abilities, age-related increases in coupling were found for a variety of ability domains. Within-person associations between primary mental abilities and cognitive flexibility were weaker and relatively stable with age. We discuss the role of speed and flexibility for cognitive aging.

Keywords: psychomotor speed; cognitive flexibility; primary mental abilities; Seattle Longitudinal Study; cognitive aging; longitudinal; within-person coupling

1. Introduction

The processing speed hypothesis of cognitive aging [1] states that declines in processing speed underlie age-related changes in fluid cognitive performance. Evidence in support of the hypothesis has been primarily obtained using a between-person approach—that is, relying on sample level (i.e., between persons) associations between speed and cognitive performance. Generally, these cross-sectional studies find that processing speed mediates cross-sectional age differences in cognitive performance (for a meta-analysis, see [2]). However, in longitudinal data, the between-person and within-person associations between speed and cognitive performance are not as strong and leave room for alternative explanations [3–17]. It has also been proposed that declines in attentional flexibility, defined as the ability to switch between task sets, is responsible for age-related changes in fluid cognitive performance [18]. Cognitive flexibility—attention switching [19] and set shifting [20,21]—may also explain intraindividual variability in cognitive performance [14]. In the present study, we use up to nine waves of longitudinal data collected over 56 years from a subsample of participants of the Seattle Longitudinal Study (SLS; [22]) to examine within-person associations of psychomotor speed and cognitive flexibility with cognitive aging of primary mental abilities.

1.1. Processing Speed and Cognitive Aging: Between-Person and within-Person Perspectives

According to the processing speed hypothesis [1], age-related decline in fluid cognition is driven by declines in processing speed. Studies of cross-sectional between-person age differences in fluid cognitive performance generally find that these differences are mediated by processing speed. Summarizing this literature, Verhaeghen and Salthouse's meta-analysis [2] found that 79% of age-related variance in reasoning (fluid), 72% of age-related variance in space (visualization), and 71% of age-related variance in episodic memory (memory) was shared with speed. Of course, findings based on cross-sectional age variance extractions are not always valid representations of the structure of longitudinal age-related change [23,24]. Longitudinally, changes in processing speed are usually correlated with changes in fluid cognitive performance, meaning that those individuals who showed more decline than their peers in processing speed also showed more decline than their peers in fluid cognitive performance [3,8–10,15–17]. However, the strength of the association was typically lower than seen in the cross-sectional studies.

In addition to examining between-person associations of longitudinal changes between processing speed and other indicators of fluid cognitive performance, some studies examined between-person lead–lag associations [4–7]. According to the processing speed hypothesis, change in processing speed is responsible for cognitive decline. Therefore, changes in processing speed should precede changes in other cognitive abilities. That is, those who perform worse than others in processing speed at a given measurement wave would show more decline over the next period in another cognitive test. These studies generally found that earlier levels of processing speed predicted subsequent change in cognitive performance, with some studies finding the lead–lag association only with fluid cognitive performance [4,7], and others finding lead–lag associations also with crystallized cognitive performance [5,6].

Taken all together, previous research based on analysis of between-person associations indicates that speed is associated with cognitive ability, and that this association is typically stronger when looking at links at performance at a single occasion (cross-sectional) than when looking at longitudinal changes. Furthermore, findings regarding lead–lag associations suggest a temporal link between processing speed and (subsequent) changes in cognitive performance, with some indication that those influences pervade both fluid and crystallized abilities.

Notably, the mechanisms driving associations between processing speed and cognitive performance are assumed to operate within-person (see [1]). As processing speed declines, individuals are assumed to perform less effectively on cognitive tasks because (a) cognitive processes cannot be executed within given time limits; and (b) because information from earlier processing steps are not available for higher-order processes that require simultaneous integration of information. Salthouse [1] draws from (a) "assembly line" and (b) "juggling" metaphors to illustrate these mechanisms: (a) a task needs to be completed before available time runs out; and (b) a task will not be executed successfully if constituent tasks are not completed on time. As individuals age, these processing constraints exert more and more pressure on cognitive performance. From a within-person perspective, the hypothesis is that when a person scores lower than usual on a test of processing speed, he or she will also perform lower than usual on other tests of cognitive performance. At the extreme end of the within-person perspective, relative rank compared to other persons is irrelevant.

Some studies have indeed examined associations between processing speed and cognitive performance from a within-person perspective. Using processing speed as a time-varying predictor, these studies generally found within-person associations between processing speed and cognitive performance [11–13]. However, processing speed did not account for all of the longitudinal age-related changes in cognitive performance. Systematic long-term change was still evident after controlling for the within-person changes in speed in the multi-year cognitive performance trajectories. Taken together, studies focusing on within-person associations generally suggest that there may be links between processing speed and fluid cognitive performance.

A different view of the within-person associations emerges in studies examining within-person associations in daily data [14]. Cognitive variability over different time scales (e.g., trial-to-trial, block-to-block, day-to-day, year-to-year) may be based on different processes and show distinct associations with other variables [25,26]. At the faster time scale in daily data, day-to-day changes in fluid cognitive performance measured in a test of working memory were not associated with day-to-day changes in processing speed within persons [14]. Instead, day-to-day changes in working memory were linked with cognitive flexibility (measured as performance on an attention switching task), as we will explain in more detail below.

In addition to suggesting that processing speed and cognitive ability are linked within-person, the processing speed hypothesis [1] indicates that this link should get stronger with age. The meta-analysis by Verhaeghen and Salthouse [2] found that associations between speed and performance on a variety of cognitive tests were stronger at older ages. In particular, the association was stronger among adults older than 50 years than among adults younger than 50 years, the implication being that cognitive slowing constrained older adults' performance on a wide range of fluid cognitive tasks. Relatively less is known regarding whether within-person associations become stronger with age.

1.2. Cognitive Flexibility and Cognitive Aging: Between-Person and within-Person Perspectives

Cognitive flexibility, defined as attention switching and task shifting, declines in old age [27,28]. It has been argued that individual differences in cognitive flexibility could be responsible for age-related changes in other cognitive abilities. For example, Stankov (1988) [18] found that cross-sectional age differences in fluid cognitive performance were no longer reliably different from zero after controlling for attentional flexibility, a latent factor reflecting individual differences in the ability to change mental sets. Compared to processing speed, cognitive flexibility received relatively less attention as an explanatory variable in cognitive aging. However, as noted in the previous section, Stawski and colleagues (2013) [14] found that day-to-day changes in working memory were linked with cognitive flexibility. Although differences in processing speed were linked to between-person differences in working memory, they were not linked to day-to-day changes. Based on this finding, the authors concluded that different mechanisms may be relevant for between-person vs within-person variability in working memory. They argued that between-person differences in processing speed may indicate individual differences in brain integrity and thus explain between-person differences in working memory performance, while attention switching may be a mechanism involved in day-to-day performance variability in working memory tasks. These findings are in line with the view of Verhaeghen and Basak (2005) [29], who proposed that switching the focus of attention is a cognitive primitive of working memory performance. It remains an open question as to whether cognitive flexibility may have within-person associations when looking at change at the slower time scale, across multiple years.

If cognitive flexibility is relevant for age-related differences in other cognitive abilities, it may be expected that within-person associations increase with age. At the between-person level, Schaie (1958) [27] reported that the correlations between cognitive flexibility and primary mental abilities were relatively stable across the adult lifespan. Stawski and colleagues [14] found no age differences in the strength of the within-person couplings between working memory, speed, and attention switching between younger (18–24 years old) and older (66–95 years old) adults. It is an open question whether the within-person coupling becomes stronger as individuals become older.

1.3. The Present Study

Our goal in the present study was to examine (a) whether within-person fluctuations in cognitive performance can be predicted by within-person fluctuations in speed and/or cognitive flexibility; and (b) whether the strength of these associations increases with age. According to the processing speed hypothesis, speed should be associated with fluid cognitive performance within persons and this association should become stronger as individuals get older. Furthermore, if cognitive flexibility is involved in cognitive performance, we should see within-person associations between cognitive flexibility and cognitive performance. In the present study, we used up to nine waves of data obtained over 56 years in the Seattle Longitudinal Study (SLS; [22]) to examine within-person associations of cognitive performance (five primary mental abilities; [30]) with psychomotor speed and cognitive flexibility.

2. Materials and Methods

The SLS is an interdisciplinary longitudinal panel study that followed participants across the entire adult life span. The study design is described in detail elsewhere [22], with details relevant to the present study included below (see also [31,32]).

2.1. Participants and Procedure

Since 1956, close to 6000 individuals between 22 and 101 years of age participated in the SLS. Participants were community-dwelling individuals in the Seattle metropolitan area and were recruited and stratified by sex and age (22–70 years old at baseline) from members of a health maintenance organization. Following a cohort-sequential design, new participants joined the study at 7 year intervals. The subsample in the present study includes participants who joined the SLS in 1956, 1963, 1970, 1977, or 1984 and provided at least five observations of psychomotor speed, cognitive flexibility, and primary mental abilities. In sum, we utilized longitudinal data obtained from N = 582 individuals on up to nine measurement occasions at 7 year intervals of up to 56 years (1956, 1963, 1970, 1977, 1984, 1991, 1998, 2005, and 2012). Table 1 provides an overview of sociodemographic characteristics for the full study sample and separately according to the year the participants joined the SLS.

Table 1. Descriptive statistics for sociodemographic variables.

Sample	*n*	Age at Baseline			% Women	Years of Education		
		M	SD	Range		M	SD	Range
Whole sample	582	40.96	10.07	21–66	59	15.00	2.63	8–20
Baseline in 1956	93	40.12	9.42	22–61	57	14.89	2.72	8–20
Baseline in 1963	153	40.34	9.13	21–64	65	14.33	2.48	8–20
Baseline in 1970	126	41.01	10.15	22–65	58	14.45	2.57	8–20
Baseline in 1977	107	42.11	11.46	23–66	52	15.72	2.45	8–20
Baseline in 1984	103	41.36	10.42	24–63	61	16.01	2.55	12–20

2.2. Measures

2.2.1. Primary Mental Abilities

Five subtests from Thurstone's Primary Mental Abilities Test (1948 PMA 11–17 version; [30]) were given to participants at every wave since the beginning of the study. Using the scores of the entire SLS sample at their first measurement occasion as reference (see [22]), we standardized the raw scores on each test to a T-score metric (M = 50, SD = 10).

In the Number Ability test, participants are presented with an arithmetic problem and are asked whether a given solution is correct. The score indicates the frequency of correct responses minus the frequency of wrong responses. In the Verbal Meaning test, participants are asked to indicate the correct synonym for words out of four given alternatives. This test measures an individual's recognition vocabulary. In the Word Fluency test, participants are asked to list as many words as possible that begin with the letter "S" (common nouns but not proper nouns) within 5 min. The score indicates the number of valid words named by the participant and indicates the ability to retrieve words from long-term storage. In the Inductive Reasoning test, participants are presented with series of alphabetic letters and are asked to indicate the letter that logically follows in the series from six alternatives. The score indicates an individual's ability to plan and to solve logical problems. In the Spatial Orientation test, participants are presented with a stimulus figure and asked to indicate out of six alternatives which figure is a rotation and not a mirror image of the stimulus figure.

Theoretical embedding: In the extended theory and model of fluid and crystallized intelligence [33,34], inductive reasoning is a measure of fluid ability, number ability is a measure of quantitative mathematical abilities, verbal meaning is a measure of crystallized ability, spatial orientation represents visualization, and fluency represents retrieval ability. According to the three-stratum theory [35], inductive reasoning represents the second-stratum factor fluid ability, number ability and verbal meaning represent crystallized ability, spatial orientation represents broad visual perception, and word fluency represents broad retrieval ability. In the Cattell–Horn–Carroll (CHC) model [36,37], inductive reasoning represents fluid ability, number ability represents quantitative knowledge, verbal meaning represents crystallized ability, spatial orientation represents visual processing, and word fluency represents long-term storage and retrieval. From a neuropsychological and executive functioning perspective, inductive reasoning is closely related to updating and working memory, and fluency is considered a measure of executive functioning [20,21].

2.2.2. Psychomotor Speed and Cognitive Flexibility

Psychomotor speed and cognitive flexibility were indicated by performance on two tests of behavioral rigidity [22] that were assessed at every wave since the beginning of the study.

Components for psychomotor speed and cognitive flexibility scores: The capitals test consists of two parts. In the first part of the test, participants are asked to copy a paragraph that contains words starting in capital letters, words spelled entirely in capital letters, or words where the first letter is spelled in lower case letters and the rest is spelled in capital letters. In the second part of the test, participants are asked to recopy the paragraph but substitute lower case letters for capital letters and vice versa. Participants are given 2.5 min for each part of the test [22]. The capital test gives two scores: copying speed, indicating the number of correctly copied words in the first part of the task, and instructional set flexibility, the proportion of number of correctly copied words in the second part of the task to the number of correctly copied words in the first part of the task [22].

In the opposites test, participants are presented three lists with 40 stimulus words each. First, participants are asked to give, in two minutes, synonyms for as many words as possible in the first list. Then, participants are asked to give, in the next two minutes, antonyms for as many words as possible in the second list. Finally, they are asked to give, again in two minutes, antonyms or synonyms depending on whether words were written in small case or capital letters. The test yields three scores: associational speed indicating number of correct responses in the first two lists, and two associational flexibility scores, indicating (a) the proportion of erroneous responses in the third list to the total number of responses in the third list; and (b) the proportion of number of correct responses in the third list to the number of correct responses in the first and second lists, respectively. Formulae to calculate the associational flexibility scores can be found elsewhere [22].

Computation of psychomotor speed and cognitive flexibility scores: A *psychomotor speed* factor score indicating the "functional efficiency in coping with familiar situations requiring rapid response and quick thinking" [19] (p. 608) was calculated for each person on each occasion as a weighted composite of the copying speed (weight = 0.60) and associational speed (weight = 0.40) scores. Similarly, a *cognitive flexibility* factor score indicating "the individual's ability to shift without difficulty from one activity to another; it is a measure of effective adjustment to shifts in familiar patterns and to continuously changing situational demands" [19] (pp. 608–609) was calculated as a weighted composite of the instructional flexibility (weight = 0.25) and the first (weight = 0.35) and the second (weight = 0.40) associational flexibility scores [22]. For convenience of interpretation, factor scores were standardized to a T-score metric ($M = 50$, $SD = 10$) based on the first occasion scores of the entire SLS sample (see [22]). Higher scores indicate speediness and flexibility.

Theoretical embedding: In the extended theory and model of fluid and crystallized intelligence [33,34], the indicator of psychomotor speed represents processing speed, because it is based on tasks that require participants to "quickly find or state correct answers to easy problems" and to "quickly copy printed mixed upper- and lowercase letters and words" [34] (p. 77). According to the three-stratum theory [35], copying speed represents the second-stratum broad speediness factor (narrow ability: "writing speed", also a psychomotor ability: see Chapter 13) and associational speed can be considered to measure the narrow ability "rate of work in performing verbal tasks" [35] (see Chapter 11) which is related to the second-stratum broad speediness factor [35] (speed of response, see p. 634). In the CHC speed hierarchy [37,38], copying speed reflects the narrow ability "writing speed" and the second-stratum ability of "broad psychomotor speed" and associational speed is most closely related to the second-stratum ability of "broad cognitive speed" ("rate of test taking"). Psychomotor speed in the SLS is highly correlated with, but not identical to, perceptual speed [28]. Also, our measure of psychomotor speed probably reflects a different construct than "broad decision speed" [37,38], which is typically measured with simple and choice reaction time tasks. Cognitive flexibility arguably represents the broad ability of short-term memory within the CHC model of intelligence [34] (narrow ability: shifting), while it is less clear how cognitive flexibility would be classified within the extended Gf–Gc and CHC frameworks.

2.2.3. Age

Chronological age at each measurement occasion indicated the number of years since an individual's birth. This variable was coded in integer numbers and centered at 70 years, and, to facilitate interpretation of model parameters, scaled in decades. The frequencies of observations across chronological age are presented in Figure 1. As can be seen, the bulk of observations fall between age 33 (5th percentile) and 84 (95th percentile) with the results applying most pertinently in this range.

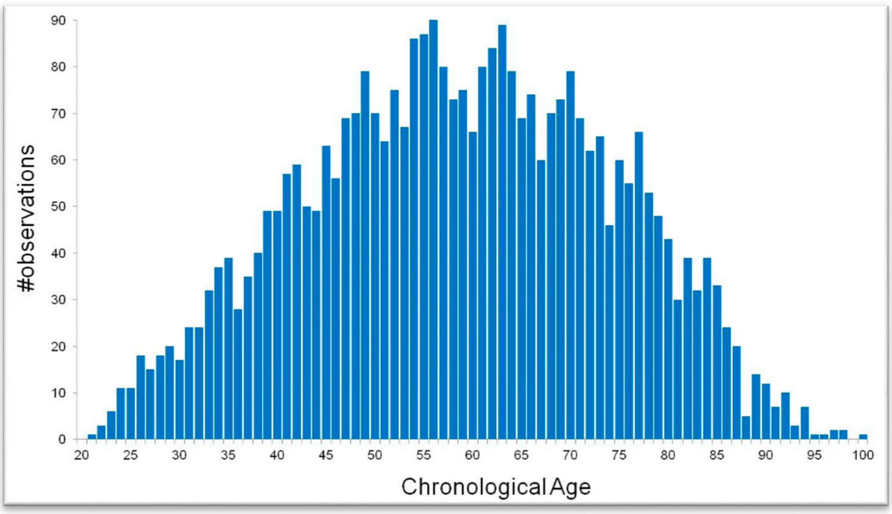

Figure 1. Frequency of longitudinal observations over age. The models included 3468 data points from 582 participants.

2.3. Data Analysis

Within-person couplings of each of the five primary mental abilities with (a) psychomotor speed and (b) cognitive flexibility were examined using multilevel models of detrended longitudinal data. Detailed description of the analytical methods can be found in elsewhere [32], with example setup given here (for within-person coupling of number ability and psychomotor speed). Second, we modeled within-person couplings and age-related changes therein.

2.3.1. Detrending

First, following standard time series analytical procedures, we detrended each individual's data [39–42], thereby removing long-term developmental trends over time-in-study (56 years) that might confound our examination of within-person coupling. Specifically, we estimated individual-level growth models wherein the outcomes were regressed on time-in-study using SAS Proc GLM [43]. For example, linear and quadratic trends in psychomotor speed and number ability were obtained and removed using the regression model,

$$number\ \ ability_t \ = \ \beta_0 + \ \beta_1(time_t) \ + \ \beta_2(time^2{}_t) \ + \ en_t \tag{1}$$

$$psychomotor\ \ speed_t \ = \ \beta_0 + \ \beta_1(time_t) \ + \ \beta_2(time^2{}_t) \ + \ ep_t \tag{2}$$

where $number\ ability_t$ and $psychomotor\ speed_t$, scores at occasion t, are a function of intercept and linear and quadratic change parameters (β_0, β_1, and β_2, respectively), and residual terms, en_t for number ability and ep_t for psychomotor speed, respectively. The residual scores ep_t and en_t then are the detrended scores used in examination of within-person couplings.

2.3.2. Within-Person Couplings

Within-person couplings of each of the primary mental abilities with psychomotor speed and cognitive flexibility, and how these couplings change with age, were then examined in a multilevel modeling framework [44] using SAS Proc Mixed [45]. For example, detrended scores for number ability were modeled as

$$en_{ti} \ = [\gamma_{10}(ep_{ti}) + u_{1i}(ep_{ti})] + [\gamma_{20}(ep_{ti} \ \times \ age_{ti}) + \gamma_{30}(ep_{ti} \ \times \ age^2{}_{ti})] + r_{ti} \tag{3}$$

where en_{ti} and ep_{ti} are detrended scores of person i for number ability and psychomotor speed at time t, γ_{10} is the prototypical within-person coupling parameter that indicates the strength of the coupling between number ability and psychomotor speed at age 70 (centering age), u_{1i} are person-specific deviations from the prototypical within-person coupling parameter γ_{10}. For example, if person i would show a stronger within-person coupling between number ability and psychomotor speed than the sample average (as indicated by γ_{10}), then u_{1i} would be positive. If person i would show a weaker within-person coupling than the typical participant, then u_{1i} would be negative. γ_{20} and γ_{30} indicate the prototypical linear and quadratic age-related rates of change in the within-person coupling. Note that because the number of observations per participant was relatively low, we did not model between-person differences in age-related linear and quadratic rates of change (i.e., u_{2i} and u_{3i}), a point we shall return to in the discussion. For illustration, Figure 2 shows how within-person coupling of psychomotor speed and number ability may differ across persons and/or age: Panel A shows the detrended time series of psychomotor speed and number ability for a participant with relatively low within-person coupling ($\gamma_{10} + u_{1i} = 0.006$) and Panel B shows the time series for a participant with relatively high within-person coupling ($\gamma_{10} + u_{1i} = 1.049$). Pseudo-$R^2$ was calculated as the percentage reduction in residual variance after accounting for within-person couplings with psychomotor speed and cognitive flexibility, respectively, and linear and quadratic age-related changes therein.

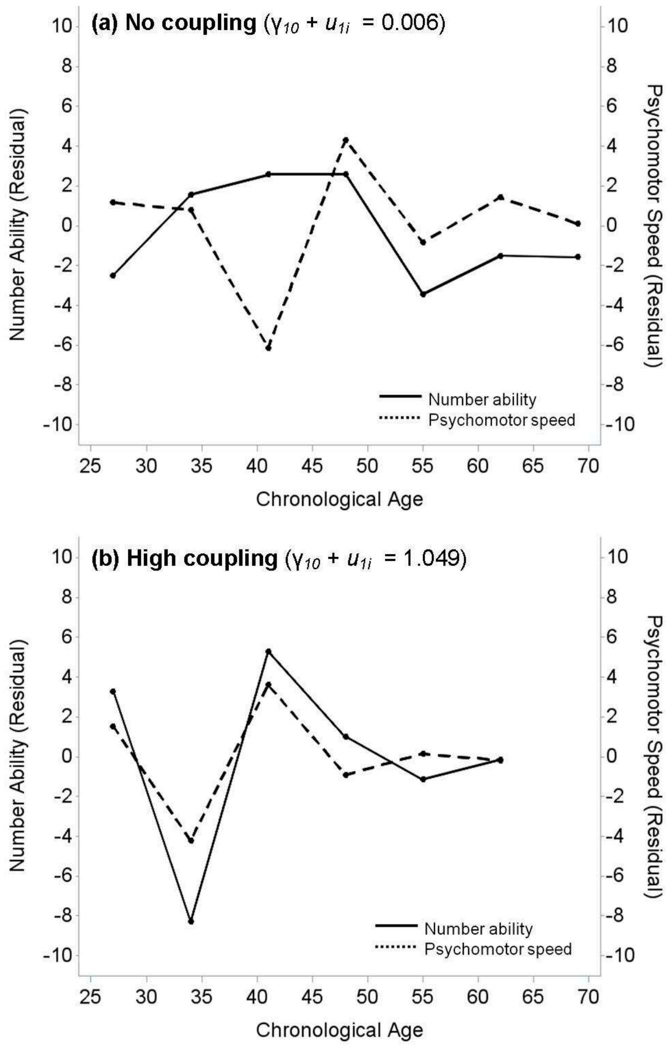

Figure 2. Detrended time series of psychomotor speed and number ability for two participants. (**a**) No coupling from psychomotor speed to number ability ($\gamma_{10} + u_{1i}$ = 0.006); (**b**) high level of coupling from psychomotor speed to number ability ($\gamma_{10} + u_{1i}$ = 1.049).

3. Results

3.1. Within-Person Coupling between Primary Mental Abilities and Psychomotor Speed

Results from the models examining within-person couplings between the five primary mental abilities and psychomotor speed and how these couplings change with age are shown in Table 2. The average within-person coupling parameter γ_{10} indicates the extent to which fluctuations of a primary mental ability can be predicted by psychomotor speed. For example, the γ_{10} = 0.177 indicates the extent of coupling between number ability and psychomotor speed for the typical participant at age 70 years (centering age). That is, when a participant scored 1 unit higher in psychomotor speed than was expected, based on his or her longitudinal trajectory, his or her score on the test of number ability was also 0.177 units higher than expected. The γ_{10} parameters in all five models were reliably different from 0 (range 0.090 to 0.201, $p < 0.05$), indicating that, on average, psychomotor speed was coupled with all the primary cognitive abilities at the within-person level (at age 70 years), with the extent of coupling differing across persons ($\sigma^2_{u1} \geq 0.210$, $p < 0.05$). Within-person couplings with psychomotor speed and linear and quadratic age-related changes therein explained 16%–21% of within-person variance in detrended primary mental abilities.

Table 2. Multilevel model examining age-related change in the within-person coupling of primary mental abilities and psychomotor speed.

Primary Mental Ability	Coupling Parameter γ_{10} (SE)		Linear Age Change in the Coupling Parameter γ_{20} (SE)		Quadratic Age Change in the Coupling Parameter γ_{30} (SE)		Variance of the Coupling Parameter σ^2_{u1} (SE)		Residual Variance σ^2_e (SE)		Pseudo R^2
Number Ability	0.177 *	(0.034)	0.047 *	(0.023)	0.010	(0.008)	0.229 *	(0.030)	6.297 *	(0.166)	18%
Verbal Meaning	0.201 *	(0.036)	0.067 *	(0.023)	0.013	(0.008)	0.274 *	(0.037)	6.156 *	(0.167)	20%
Word Fluency	0.108 *	(0.040)	−0.010	(0.026)	0.005	(0.009)	0.340 *	(0.043)	8.136 *	(0.216)	20%
Inductive Reasoning	0.106 *	(0.031)	0.044 *	(0.020)	0.013	(0.007)	0.210 *	(0.025)	4.527 *	(0.120)	21%
Spatial Orientation	0.090 *	(0.038)	0.087 *	(0.026)	0.031 *	(0.009)	0.265 *	(0.037)	8.115 *	(0.215)	16%

Note: N = 582. Scores for psychomotor speed and primary mental abilities were scaled in a T metric (M = 50, SD = 10) based on first occasion data of the entire Seattle Longitudinal Study (SLS) sample. Unstandardized estimates, standard errors in parentheses. Chronological age was centered at 70 years and scaled in decades to facilitate interpretation. Each primary mental ability was predicted by psychomotor speed at the within-person level, with γ_{10} indicating the prototypical within-person coupling; γ_{20} and γ_{30} indicate rate of age-related linear and quadratic change in the coupling parameter per decade; σ^2_{u1} is the variance of the within-person coupling parameter γ_{10}, and σ^2_e is the residual variance. Pseudo-R^2 was calculated as the percentage reduction in residual variance after controlling for within-person couplings with psychomotor speed and linear and quadratic age changes therein. * $p < 0.05$.

There was also evidence of systematic age-related change in the within-person coupling. Specifically, the γ_{20} parameters indicate rate of age-related linear change in the within-person coupling parameters. For example, the linear age parameter describing change in the within-person coupling of number ability and psychomotor speed is $\gamma_{20} = 0.047$ units per decade, indicating that the age 70 coupling parameter of $\gamma_{10} = 0.177$ increased to $0.177 + 0.047 = 0.224$ at age 80 (quadratic trends not taken into account). Thus, for the average participant at 80 years of age, when psychomotor speed score was 1 unit higher than expected based on his or her longitudinal trajectory, his or her number ability was 0.224 units higher than expected. Table 2 shows evidence of systematic age-related linear increases in the within-person coupling for number ability ($\gamma_{20} = 0.047$), verbal ability ($\gamma_{20} = 0.067$), inductive reasoning ($\gamma_{20} = 0.044$), and spatial orientation ($\gamma_{20} = 0.087$), but not for word fluency ($\gamma_{20} = -0.010$). Significant quadratic curvature in the age-related changes was only evident for spatial orientation ($\gamma_{30} = 0.031$), indicating that the within-person coupling was slightly stronger at both ends of the adult lifespan, and slightly weaker in the middle. We note that this pattern may be based on fewer observations being available at both ends of the lifespan (see Figure 1). This may result in stronger curvature observed at these points when fitting a polynomial model with a quadratic term. Visual depictions of the age-related changes in within-person coupling are shown in Figure 3. In sum, (a) all primary abilities showed within-person associations with psychomotor speed; (b) the strength of the coupling increased linearly with age for all primary mental abilities with the exception of word fluency; and (c) with some curvature for spatial orientation.

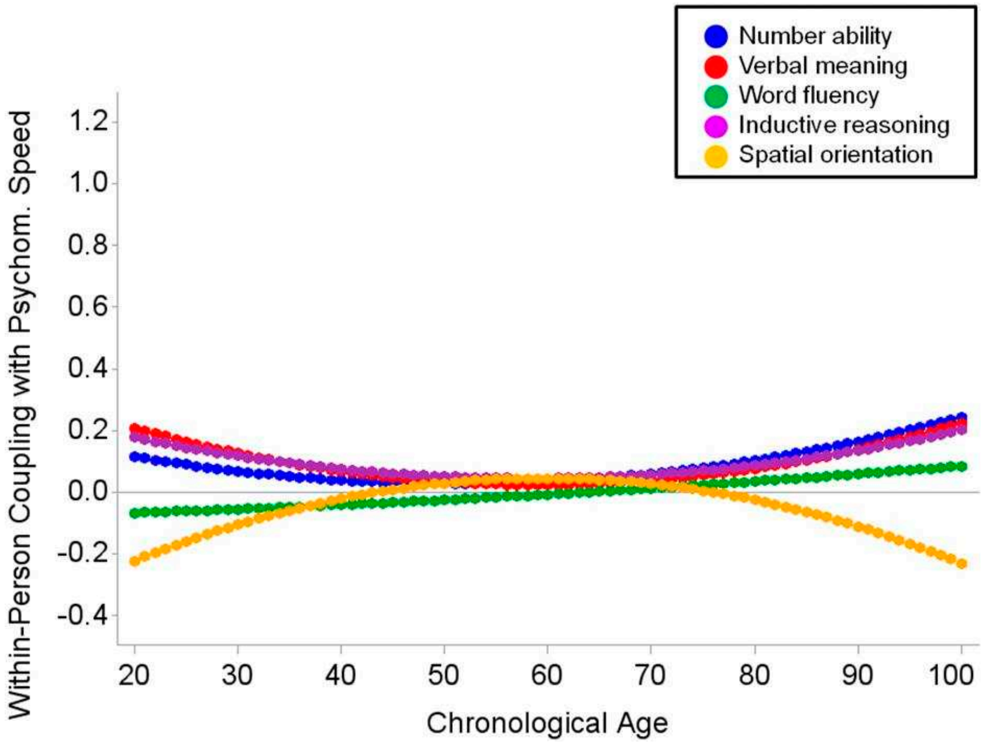

Figure 3. Within-person coupling parameters (γ_{10}) across chronological age for psychomotor speed and primary mental abilities. All primary mental abilities were associated with psychomotor speed within persons at age 70 years and within-person associations with psychomotor speed linearly increased with age for all primary mental abilities with the exception of word fluency. Furthermore, quadratic age trends were observed for spatial orientation.

3.2. Within-Person Coupling between Primary Mental Abilities and Cognitive Flexibility

Results from the models examining within-person couplings between the five primary mental abilities and cognitive flexibility and how these couplings change across chronological age are shown in Table 3. The interpretation of the parameters is the same as above. For the prototypical individual at age 70 (centering age), there was evidence that number ability (γ_{10} = 0.060) and inductive reasoning (γ_{10} = 0.057) were systematically linked to cognitive flexibility, but the other primary mental abilities were not. As before, there were between-person differences in the strength of the within-person couplings ($\sigma^2{}_{u1} \geq 0.095$, $p < 0.05$) and evidence of a systematic linear age-related increase in the within-person couplings between number ability and cognitive flexibility (γ_{20} = 0.034). Although the age-related changes were not significant for the other primary mental abilities, there was hint of quadratic age-related change for verbal meaning (γ_{30} = 0.012) and spatial orientation ($\gamma_{30} = -0.017$). For verbal meaning, the quadratic effect was positive, indicating that the within-person coupling was slightly stronger at both ends of the adult lifespan and slightly weaker in the middle. For spatial orientation, the quadratic effect was negative, indicating that the within-person coupling was slightly weaker at the ends of the adult lifespan and stronger in the middle. Again, the stronger curvature at both ends of the age span may be based on the scarcity of observations at the extremes of the distributions. Within-person couplings with cognitive flexibility and linear and quadratic age-related changes therein explained 14%–19% of within-person variance in detrended primary mental abilities. Visual depictions of the age-related changes in within-person coupling are shown in Figure 4. In sum, there was little evidence for within-person couplings between primary mental abilities and cognitive flexibility and linear-age related changes therein; with relatively small within-person coupling for number ability and inductive reasoning and small linear (for number ability) or quadratic change (for verbal meaning and spatial orientation) across the adult lifespan.

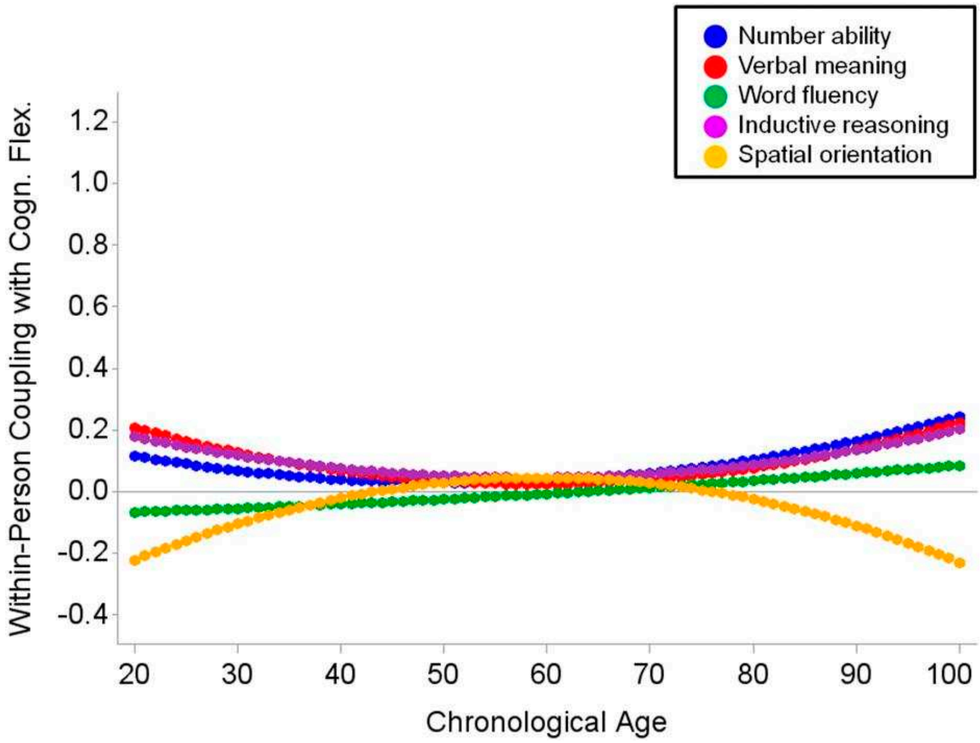

Figure 4. Within-person coupling parameters (γ_{10}) across chronological age for cognitive flexibility and primary mental abilities. Cognitive flexibility was associated with number ability and inductive reasoning within persons at age 70 years. Linear increase in within-person coupling with cognitive flexibility was observed for number ability, quadratic age trends were observed for verbal meaning and spatial orientation.

Table 3. Multilevel model examining age-related change in the within-person coupling of primary mental abilities and cognitive flexibility.

Primary Mental Ability	Coupling Parameter γ_{10} (SE)		Linear Age Change in the Coupling Parameter γ_{20} (SE)		Quadratic Age Change in the Coupling Parameter γ_{30} (SE)		Variance of the Coupling Parameter σ^2_{u1} (SE)		Residual Variance σ^2_e (SE)		Pseudo R^2
Number Ability	0.060 *	(0.023)	0.034 *	(0.016)	0.009	(0.006)	0.095 *	(0.014)	6.543 *	(0.172)	15%
Verbal Meaning	0.038	(0.026)	0.026	(0.016)	0.012 *	(0.006)	0.168 *	(0.023)	6.239 *	(0.172)	19%
Word Fluency	0.013	(0.028)	0.021	(0.019)	0.001	(0.007)	0.149 *	(0.023)	8.649 *	(0.233)	14%
Inductive Reasoning	0.057 *	(0.021)	0.021	(0.014)	0.009	(0.005)	0.089 *	(0.012)	4.759 *	(0.126)	17%
Spatial Orientation	0.027	(0.029)	−0.035	(0.018)	−0.017 *	(0.006)	0.196 *	(0.025)	7.775 *	(0.210)	19%

Note: N = 582. Scores for cognitive flexibility and primary mental abilities were scaled in a T metric (M = 50, SD = 10) based on first occasion data of the entire SLS sample. Unstandardized estimates, standard errors in parentheses. Chronological age was centered at 70 years and scaled in decades to facilitate interpretation. Each primary mental ability was predicted by cognitive flexibility at the within-person level, with γ_{10} indicating the prototypical within-person coupling; γ_{20} and γ_{30} indicating rate of age-related linear and quadratic change in the coupling parameter per decade; σ^2_{u1} is the variance of the within-person coupling parameter γ_{10}; and σ^2_e is the residual variance. Pseudo-R^2 was calculated as the percentage reduction in residual variance after controlling for within-person couplings with cognitive flexibility and linear and quadratic age changes therein. * $p < 0.05$.

4. Discussion

This study examined within-person associations of five primary mental abilities with psychomotor speed and cognitive flexibility. Our findings indicate that psychomotor speed was linked to primary mental abilities *within-persons*. That is, when a person performed better than usual on a test of psychomotor speed as expected based on his or her developmental trajectory, he or she also performed better than usual on all five tests of primary mental abilities. In line with predictions of the processing speed hypothesis [1], there was also some evidence for age-related increases in the strength of the within-person coupling with psychomotor speed. Age-related increases in the within-person coupling with psychomotor speed were observed for number ability, verbal ability, inductive reasoning, and spatial orientation. In contrast, there was relatively little evidence of systematic within-person associations between links between cognitive flexibility and the primary mental abilities (exception of number and reasoning ability) or systematic age-related change in the couplings. Below, we discuss possible factors underlying these findings.

4.1. Within-Person Associations of Psychomotor Speed and Cognitive Flexibility with Primary Mental Abilities

According to the processing speed theory of cognitive aging [1], processing speed becomes an increasingly critical factor for cognitive performance with age. Our study provided some evidence for this hypothesis by showing that all primary mental abilities were indeed linked with psychomotor speed, within-persons, when people were 70 years old. The strength of this within-person association generally increased with age for four of five primary mental abilities, including number ability and verbal meaning—aspects of crystallized cognitive ability, and spatial orientation—a visualization ability [46,47]. However, the processing speed theory is primarily focused on the link between age-related declines in speed and age-related declines in fluid cognitive performance. Thus, our findings on age-related increases in within-person couplings with speed for primarily crystallized measures stretch a bit beyond the theory-based hypotheses. It is important to note that the two crystallized measures used here, number ability and verbal meaning tests (particularly as assessed by Thurstone's PMA measures), are highly speeded tests when compared to other measures of these abilities [22,48]. Thus, the couplings may, in part, reflect a "performance-specific confound" rather than a "construct-relevant" association [48,49]. For example, Wilhelm and Schulze (2002) [50] reported that mental speed showed stronger associations with a reasoning test when it was administered under a time limit ($r = 0.49$) than when it was administered without a time limit ($r = 0.34$). Taken together, our findings on within-person associations between primary mental abilities and psychomotor speed generally supported the processing speed theory, while some findings went beyond predictions based on this theory.

The dedifferentiation hypothesis of cognitive aging proposes that the structure of cognitive abilities becomes compressed (less differentiated) in advanced ages [51]. This would manifest as stronger associations between cognitive abilities in older as compared to younger individuals (between-persons) or as associations becoming stronger as individuals get older (within-persons). A recent study using data from the SLS supported the dedifferentiation hypothesis by demonstrating an age-related increase in within-person couplings among primary mental abilities [32]. Deteriorations in biological resources [52,53] and deteriorations in more basal cognitive processes, such as speed [49], have been proposed as mechanisms underlying cognitive dedifferentiation. The findings of the present study show that some primary mental abilities become more strongly coupled with psychomotor speed as people get older and suggest that speed may be a candidate variable to explain cognitive dedifferentiation at the within-person level.

In the present study, cognitive flexibility did not predict primary mental abilities at the within-person level, with the exception of number ability and inductive reasoning. Cognitive flexibility as measured in the SLS represents set shifting or attention switching. This pattern of findings is different from the findings of Stawski and colleagues [14] who reported that processing speed did not predict cognitive performance within-persons, but attention switching did. Differences in methodological approaches of these two studies could potentially explain the discrepancy between findings. First, Stawski and colleagues [14] examined day-to-day fluctuations of cognitive performance, whereas we examined fluctuations around the individual developmental trajectory that spanned over many years. As noted in the introduction, intraindividual variability over different time scales may be caused by different processes [25,26]. Thus, cognitive variability over different time scales may show different associations with other variables. Day-to-day variability in cognitive performance may be (partially) caused by, for example, lapses of attention or ability to focus, which are related to executive functions like cognitive flexibility. On the other hand, variability over longer time frames, such as seven years in the present study, may be caused by processing speed, which arguably reflects global health and brain function [14]. Therefore, it is possible that cognitive flexibility is more relevant for explaining day-to-day variability, whereas psychomotor speed is more relevant for long-term variability. Second, Stawski and colleagues [14] examined within-person associations between speed and working memory, whereas we examined within-person associations with a variety of primary mental abilities. For example, inductive reasoning, assessed in this study, is closely related to the construct of working memory, and was one of the two primary mental abilities for which we found a coupling with cognitive flexibility. Inductive reasoning/working memory and cognitive flexibility have both been identified as components of executive functions. Also, it has been proposed that processes related to cognitive flexibility, task switching, and attention switching are strongly involved in working memory (e.g., [54]). Thus, working memory may be more closely related to cognitive flexibility than primary mental abilities. Taken together, cognitive flexibility did not emerge as a powerful predictor of within-person fluctuations of primary mental abilities in our study.

4.2. Limitations and Outlook

To put the findings in perspective, we note several limitations of our study. First, because our study involved relatively few observations per person, we were not able to examine between-person differences in how within-person associations between primary mental abilities, psychomotor speed, and cognitive flexibility change with age. Further work is needed to parse out how the age trends in within-person associations differ across persons. For example, we used cohort-sequential data where participants were measured over the same age ranges in different time periods (see Table 1) and thus belonged to different birth-year cohorts. Cohort differences in longitudinal trajectories of cognitive performance are well-documented in the SLS [31,55]. Our detrending procedure accounted for any individual differences in levels of performance and in rates of linear and quadratic change, including those associated with birth-year cohort. However, cohort differences may also exist in how the coupling with psychomotor speed and cognitive flexibility changes with age. Second, the measures have some limitations. Specifically, our measure of speed involved a motor component, and this was an indicator of psychomotor speed ability rather than a pure measure of processing speed. Also, as noted above, the supposedly crystallized measures of number ability and verbal meaning tests in the present study are highly speeded measures [22,48]. Associations with psychomotor speed may be weaker with more cognitively demanding tasks measuring verbal and numerical ability. For example, in the number ability task, participants had to judge whether additions of 60 simple sums were correct and had 6 min to do so (3.6 s per item). One may expect that participants would have been able to solve a much higher proportion of the items if there was no time limitation. Therefore, under time constraints, individual as well as intraindividual differences in performance may have depended on whether one can solve the task quickly or not. In contrast, participants may not be able to solve a complex numerical task even if they have unlimited time. Thus, variation in performance in a cognitively more demanding task may depend more strongly on crystallized numerical knowledge than on speed. Furthermore, the cognitive flexibility score was based on ratio scores, which can at best be as reliable as the constituent scores. Thus, the lack of within-person associations with cognitive flexibility may also be based on the lower reliability of the cognitive flexibility scores. Also, the psychomotor speed measure was not a pure indicator of speed, but also involved other components (for example, verbal skills in the analogies task). In addition, indicators of psychomotor speed and cognitive flexibility were calculated based on the performance on the same tasks, therefore they are not independent measures. This precluded examining the within-person effects of psychomotor speed and cognitive flexibility simultaneously. Third, the data are limited in that they only provide for analysis of fluctuations in performance that manifest across 7 year intervals. As discussed above, different processes and associations may manifest at different time scales. An interesting side effect of working at this time scale is that we have necessarily assumed within-person homogeneity in variance of cognitive performance across approximately 50 years. There is some possibility that differences in variance may be related to differences in coupling (through restriction-of-range effects). Data collected at shorter intervals, and using measurement burst designs, will provide for separation and examination of both age-related changes in intraindividual variability and intraindividual coupling.

5. Conclusions

The current study adds to previous work on associations between speed, cognitive flexibility, and cognitive performance by explicitly examining within-person associations and age-related changes in those associations. Our findings show that psychomotor speed predicted all primary mental abilities within persons, whereas associations with cognitive flexibility were weaker. Furthermore, four out of five within-person couplings between primary mental abilities and psychomotor speed increased with age, whereas within-person associations between primary mental abilities and cognitive flexibility were relatively stable with age. Next steps include identifying the specific biological and psychological mechanism that may drive the within-person associations between speed and cognitive performance.

Author Contributions: SLW and KWS developed the study concept and design. GH performed the data analysis and interpretation in cooperation with NR and DG. GH drafted the manuscript and all authors provided critical revisions. All authors approved the final version of the manuscript for submission.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviation is used in this manuscript:

SLS Seattle Longitudinal Study

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